Search for hadronic axions using axioelectric effect

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We made a search for hadronic axions which could be emitted from the Sun in M1 transitions between the first 14.4 keV thermally excited and the ground state in ^{57}Fe, and absorbed in the HPGe detector by axioelectric effect. An upper limit on hadronic axion mass of 400 eV is obtained at the 95% confidence level.

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Axions arise as a result of spontaneous breaking of the Peccei–Quinn (PQ) chiral symmetry [1]. This symmetry was introduced to resolve the strong CP problem associated with the Θ–vacuum structure of QCD. The solution predicts the existence of a neutral spin–zero pseudoscalar particle, called axion, with a non–zero mass m_a. The axion mass can be interpreted as a mixing of the axion field with pions and is related to the PQ symmetry breaking scale f_a by $m_a f_a \approx m_\pi f_\pi$ where $m_\pi = 135$ MeV is the pion mass and $f_\pi = 93$ MeV its decay constant. The axion mass, or the PQ symmetry breaking scale, is arbitrary and all values solve the strong CP problem. The original PQ suggestion that f_a is equal to the electroweak symmetry breaking scale of 250 GeV, which requires an axion mass m_a of few hundred keV was quickly ruled out by experiment. The constrains on the axion mass from various laboratory experiments, astrophysics and cosmology restrict the masses of axion to a narrow 10^{-5}eV $\leq m_a \leq 10^{-2}$eV range. New axion models are introduced with breaking scale f_a at values of 10^{10}–10^{12} GeV which escapes all the phenomenological constrains. Therefore, all axion couplings become extremely small and axion models of this type are referred to as invisible axion models. Two classes of invisible axion models have been developed: KSVZ (Kim, Shifman, Vainshtein and Zakharov) or hadronic axion [2] and DFSZ (Dine, Fischler, Srednicki and Zhitnitsky) or GUT axion [3] model.

The main difference between KSVZ and DFSZ axions is that the former have no tree–level couplings to ordinary quarks and leptons because new fermions have been introduced that carry the PQ charge while usual quarks and leptons do not. As a result, the interaction of KSVZ–type axions with electrons is strongly suppressed. However, their coupling to nucleons is not zero due to the axion–pion mixing which exists even if the tree–level coupling to ordinary quark vanishes. Axions are also one of the best known and most studied candidates for the cold dark matter in the Universe. Axions with mass $\approx 10^{-5}$ eV would make a significant component of cold dark matter.

Besides the 10^{10}–10^{12} GeV there is another window around 10^6 GeV. This is the window for hadronic axions only. For this window the existing constraints based on the axion–photon coupling are excluded. In Kim's composite axion models [4] the axion–photon coupling is model dependent and may be significantly reduced. It was shown by Kaplan [5] that as a result the astrophysical bounds on the axion mass are weakened and certain Kim's models allow axion mass as large as ≈ 20 eV. Other astrophysical and cosmological bounds place a lower limit on the hadronic axion mass $m_a \geq 10$ eV [6]. Recently, axions in this narrow hadronic axion mass window of 10 eV $\leq m_a \leq$ 20 eV have been proposed as candidates for hot dark matter of the Universe [7].

A possible source of axions is our Sun. Solar axion spectra would consist of the continuous part, generated through the Primakoff effect and line spectra generated mostly in nuclear M1 transitions of some nuclides. Huxton and Lee [8] have calculated axion emission rates from the Sun for the M1 transitions in ^{57}Fe, ^{55}Mn and ^{23}Na. Other convenient sources of monoenergetic solar axions are M1 transitions in ^{7}Li [9] and ^{83}Kr [10]. Estimates suggest that the highest emission rate of monoenergetic axions will be produced during the 14.4 keV M1 transition in ^{57}Fe. Moriyama [11] proposed to detect these axions using the resonant absorption process by the same nuclide in the Earth–bound laboratory. Since both emission and absorption proceed via axion–nucleon coupling this method is free from the uncertainty of the axion–photon coupling. Using this approach Krčmar *et al.* [12] obtained an upper limit of $m_a \leq 745$ eV. We have also searched for 477.6 keV and 9.4 keV axions, which were supposed to be emitted from the Sun during M1 transitions in ^{7}Li and ^{83}Kr and resonantly absorbed by the same nuclides in our laboratory. We did not observe such events and only upper limits on the hadronic axion mass of 32 keV [9] and 5.5 keV [10] at the 95% confidence level were obtained.

Other possible interactions for detecting hadronic axions are: (i) Compton conversion of an axion to a photon $a+e \to \gamma+e$, and (ii) axioelectric effect $a+e+Z \to e+Z$. Former process was first considered by Donnelly *et al.* [13] and the latter one by Zhitnitsky and Skovpen [14]. Even if there is no axion–electron coupling at the tree–level for the KSVZ models, there will be an induced axion–electron coupling at the one–loop level, which was

calculated by Srednicki [15],

$$g_{aee} = 2.2\times10^{-15} m_a(\text{eV}) N \left[\bar{c}_{a\gamma\gamma} \ln\frac{f_a}{m} - \frac{2}{3}\frac{4+Z}{1+Z}\ln\frac{\Lambda}{m} \right] . \tag{1}$$

Here N is number of generations, $Z = m_u/m_d \approx 0.55$ is the u and d quark mass ratio, $\Lambda \approx 1$ GeV is the cutoff of order of the chiral symmetry breaking scale, $\bar{c}_{a\gamma\gamma}$ is ratio of electromagnetic and color anomalies, $f_a = f_\pi m_\pi \sqrt{Z}/(m_a(1+Z))$, and m is electron mass. For the hadronic axions with mass range 10 eV $\leq m_a \leq$ 20 eV Kaplan [5] has shown that $\bar{c}_{a\gamma\gamma} = 2$. In his minimal composite axion model [4] Kim considered the case with $N = 3$. Introducing these values into (1) we obtain $g_{aee} = 6.6\times10^{-15} m_a(\text{eV})[-14.83 + 2\ln(1.176\times10^{10}/m_a(\text{eV}))]$.

Coupling of hadronic axions with electrons is much weaker than with nucleons. However, the high temperature in the Sun's interior will broaden the nuclear line width in the Sun and, in the experiments based on the resonant absorption, this reduces the effective axion flux by a factor $\Gamma_{\text{Earth}}/\Gamma_{\text{Sun}} \ll 1$; Γ_{Sun} and Γ_{Earth} are the decay widths of the same nuclear state in the Sun and in the Earth–bound laboratory. In the axion–to–photon Compton conversion and the axioelectric effect all axions emitted during nuclear transition in the Sun will contribute, and this will compensate the smallness of the axion–electron coupling constant.

Using theoretical predictions of Zhitnitsky and Skovpen [12] we estimate that for the 14.4 keV axions the cross section for the axioelectric effect is about three orders of magnitude larger than the cross section for the axion–to–photon Compton conversion process. Therefore we will further consider only the axioelectric effect. In this effect an axion dissappears and an electron is ejected from an atom. The electron carries away all the energy of the absorbed photon, minus the energy binding the electron to the atom. Zhitnitsky and Skovpen [12] calculated cross sections for the axioeffect for atoms with $Z \ll 137$, for small axion masses and for the axion energy large compared to the K–electron binding energy. For the cross section on the K–electron they obtained

$$\sigma_{ae\to e} = \frac{8\pi\alpha_{ae}}{m^2}(Z\alpha m)^5 \frac{p_e}{k_a}\left[\frac{4\omega(\omega^2+m_a^2)}{(k_a^2-p_e^2)^4} - \frac{2\omega}{(k_a^2-p_e^2)^3} - \frac{64}{3}p_e^2k_a^2 m\frac{m_a^2}{(k_a^2-p_e^2)^6} - \frac{16m_a^2k_a^2\epsilon}{(k_a^2-p_e^2)^5} - \frac{\omega}{p_ek_a}\frac{1}{(k_a^2-p_e^2)^2}\ln\left(\frac{p_e+k_a}{p_e-k_a}\right)\right] , \tag{2}$$

where $\alpha = e^2/(4\pi) = 1/137$, $\alpha_{ae} = g_{aee}^2/(4\pi)$; ω, k_a and ϵ, p_e are the energy and the absolute value of the momentum of the axion and the ejected electron, respectively.

In the case of $m_a \to 0$ and for axion energies $\epsilon \ll m$ the cross section becomes

$$\sigma_{ae\to e} = \sqrt{2}\left(\frac{\alpha_{ae}}{\alpha}\right)\left(\frac{8\pi}{3}\frac{\alpha^2}{m^2}\right)\alpha^4 Z^5\left(\frac{m}{\omega}\right)^{\frac{3}{2}} . \tag{3}$$

In our investigations of solar hadronic axions we have searched for a peak at 14.4 keV in a single spectrum recorded in a HPGe detector. If observed, this peak could be interpreted as the result of the axioelectric effect of the 14.4 keV axions on germanium atoms, with subsequent absorption of the emitted electrons and accompanying x rays in the crystal. The 14.4 keV axions are supposed to be emitted from the Sun in M1 transition between the first thermally excited state and the ground state in ^{57}Fe. In this experimental set–up the target and the detector are the same and the efficiency of the system is substantially increased. ^{57}Fe is one of the stable isotopes of iron (natural abundance 2.2%) which is exceptionally abundant among heavy elements in the Sun (solar abundance by mass fraction 2.7×10^{-5}). Also the 14.4 keV level is relatively easy to excite thermally because its energy is comparable with the temperature in the Sun core (≈ 1.3 keV). The axion flux from the Sun was estimated by Moriyama [11] using similar calculation as in Ref. [8]. He obtained the value of $d\Phi(\epsilon)/d\epsilon = 1.7\times10^{10}\times m_a^2(\text{eV})\text{cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$. As a result of the Doppler broadening in the Sun the estimated width of the 14.4 keV peak is $\Gamma_{\text{Sun}} \approx 5$ eV. Therefore the total flux of 14.4 keV axions is expected to be $\Phi = 8.5\times10^7 m_a^2(\text{eV})\text{cm}^{-2}\text{s}^{-1}$.

In the search for the 14.4 keV peak we have re–analyzed single spectra accumulated in the HPGe detector during our investigation of solar hadronic axions using ^{7}Li. These axions were suggested to be created in M1 transitions between the first excited 478 keV and the ground state in ^{7}Li and were expected to excite resonantly the same energy level in the ^{7}Li target, placed in the laboratory. The subsequently emitted gamma rays were searched for in a HPGe detector. Run spectra were obtained with the 56.72 g lithium target placed in front of the detector while for the background spectra the lithium target was replaced with an appropriate absorber simulating background conditions. Run and background were both counted during the collection time $t = 111.11$ days each. Attenuation of axions in detector shieldings is negligible and we could sum both run and background spectra and improve the statistics by duplicating the data collection time. HPGe detector was placed in a 13 cm deep and 8 cm in diameter well of a 25.4 cm × 20.3 cm in diameter NaI crystal. The crystal was located inside an iron box with internal dimensions 54 × 33 × 33 cm^3 and with wall thickness ranging from 16 to 23 cm. The iron was more than 65 years old and was essentially free of ^{60}Co impurities. The box was lined outside with 1 cm thick lead. HPGe detector operated in anticoincidence mode with NaI crystal and the background events around 14.4 keV were reduced by a factor of ≈ 10.

The energy spectra accumulated for the 222.22 days are shown in Fig.1. We have obtained an energy calibration with a set of calibrated radioactive sources. The 14.4 keV peak is expected at the 55$^{\text{th}}$ channel. Energy resolution (FWHM) at this energy was estimated by extrapolating energy resolutions obtained from the higher

energy region. The FWHM at 14.4 keV was estimated to be 0.9 keV which corresponds to 3.5 channels.

We can relate the axion mass with the number N_a of counts, detected at 14.4 keV in our HPGe crystal, with the expression

$$N_a = \Phi \sigma_{ae\to e}\, 2\, N_{\mathrm{Ge}}\, \varepsilon_{14.4}\, t \ . \tag{4}$$

Number of germanium atoms in our 50 mm in diameter × 40 mm thick HPGe crystal is $N_{\mathrm{Ge}} = 3.47 \times 10^{24}$. Factor 2 is number of electrons in K–shell. The intrinsic efficiency $\varepsilon_{14.4}$ of our detector for the electrons and accompanying germanium x rays is ≈ 1. The data were collected during $t = 1.92 \times 10^7$ s. Introducing calculated g_{aee} into (2) we obtain for the cross section for the axioelectric effect on germanium atom $\sigma_{ae\to e} = 1.80 \times 10^{-50}\, m_a^2(\mathrm{eV})[-14.83 + 2\ln(1.176 \times 10^{10}/m_a(\mathrm{eV}))]^2 \mathrm{cm}^2$. Then from Eq. (4) we obtain for the expected number of the axioeffect events $N_a = 1.02 \times 10^{-10} m_a^4(\mathrm{eV})[-14.83 + 2\ln(1.176 \times 10^{10}/m_a(\mathrm{eV}))]^2$.

We could not identify a peak at 14.4 keV. For the number of axioeffect events we used the number of counts detected in 6 channels at the 14.4 keV region and obtained an upper limit of $N_a \leq 980$ events. This gives an upper limit on the hadronic axion mass of $m_a \leq 400$ eV at the 95% confidence level.

F. T. Avignone III *et al.* [16] searched for a signal of solar axions coherently converting into photons via the Primakoff effect. Their analysis yield a laboratory bound to $a\gamma\gamma$ coupling of $g_{a\gamma\gamma} < 2.7 \times 10^{-9}\mathrm{GeV}^{-1}$. The $a\gamma\gamma$ coupling is model dependent and it is given by

$$\begin{aligned} g_{a\gamma\gamma} &= \frac{\alpha}{\pi f_a}\frac{1}{2}\left[\bar{c}_{a\gamma\gamma} - \frac{2(4+Z)}{3(1+Z)}\right] \\ &= \frac{\alpha}{\pi f_a}\frac{1}{2}\left[\bar{c}_{a\gamma\gamma} - 1.954 \pm 0.036\right] \ , \end{aligned} \tag{5}$$

where the value of the second term in Eq. (5) and its error is calculated using $Z = 0.553 \pm 0.043$ [17]. For KSVZ models it is easy to construct models in which $\bar{c}_{a\gamma\gamma} = 2$ [5]. This leads to great suppression of axion–photon coupling $g_{a\gamma\gamma}$ because of a cancellation between two terms in Eq. (5) [5]. Moreover, Particle Data Group [18] quotes $0.3 < Z < 0.7$ allowing even vanishing axion–photon coupling. In KSVZ models the axion–electron coupling is radiatively induced at the one–loop level [15]. The corresponding diagrams are logarithmically divergent. The different cutoff scales of the part proportional to E/N and the part proportional to $2(4+Z)/[3(1+Z)]$ result in an axion–electron coupling g_{aee}, Eq. (1), which remains finite even in the case when $g_{a\gamma\gamma}$ is very small (or possibly vanish). In this particular case our measurement, based on axion–electron interaction, gives an upper limit to the hadronic axion mass which is rather insensitive to the value of Z, while the result of Ref. [16] cannot give reliable prediction about hadronic axion mass.

Because the number of detected gamma rays is proportional to the fourth power of axion mass it is very difficult to improve the sensitivity of the detection system. One should have a detector of much larger volume and, at the same time, the background in the 14.4 keV region should be reduced by a very large factor. An obvious choice would be a large volume gaseous Time Projection Chamber (TPC). One such detector is the STAR experiment's TPC currently operating at the Relativistic Heavy Ion Collider (RHIC) in Upton, USA. This TPC is 4 m long × 4 m in diameter [19] and is filled with an Ar + CH_4 mixture operating under atmospheric pressure. The active drift time of this device is ∼50 microseconds while the readout time is presently 10 milliseconds. This ratio reduces the overall efficiency of this system by about 200. In an axioelectric effect with the 14.4 keV axion, an electron with ∼ 11 keV will be emitted together with argon x rays. The electron will be stopped within ∼ 0.3 cm of the gas and will thus give a clear, pointlike signal in the volume of the TPC. The energies of the argon x rays are too low and will escape undetected. The pointlike nature of the electron signal as well as its narrow energy is expected to be easily distinguished from other background sources (*i.e.* cosmic rays and other higher momentum particles) which leave an easily recognizable extended track segment. The STAR TPC is surrounded by standard scintillator strips along the whole outer surface of the barrel as well as scintillator panels covering a part of the detector's base. These auxiliary detectors could be used in anti–coincidence (*i.e.* as a veto against charged tracks traversing the volume of the TPC) during STAR's normal data taking periods (almost 6 months/year) thus enabling a parasitic axion search while the STAR TPC is actively involved in RHIC's heavy–ion program. The sensitivity on the axion mass of ∼ 210 eV could be reached under reasonable assumptions of ∼ 1 background count/day operating for 1 year with the STAR TPC.

In the near future the STAR collaboration is expected to improve the data–acquisition readout time of the TPC by a factor < 50 which would then considerably increase the efficiency of the proposed measurement. Because the axioeffect cross section is proportional to Z^5 the efficiency of the system could be further improved by filling the TPC with the krypton gas. In that case if the TPC operates for one year with the background rate of ≈ 1 count/day, we would obtain an upper limit on m_a of ≈ 10 eV, which would close this hadronic axion mass window.

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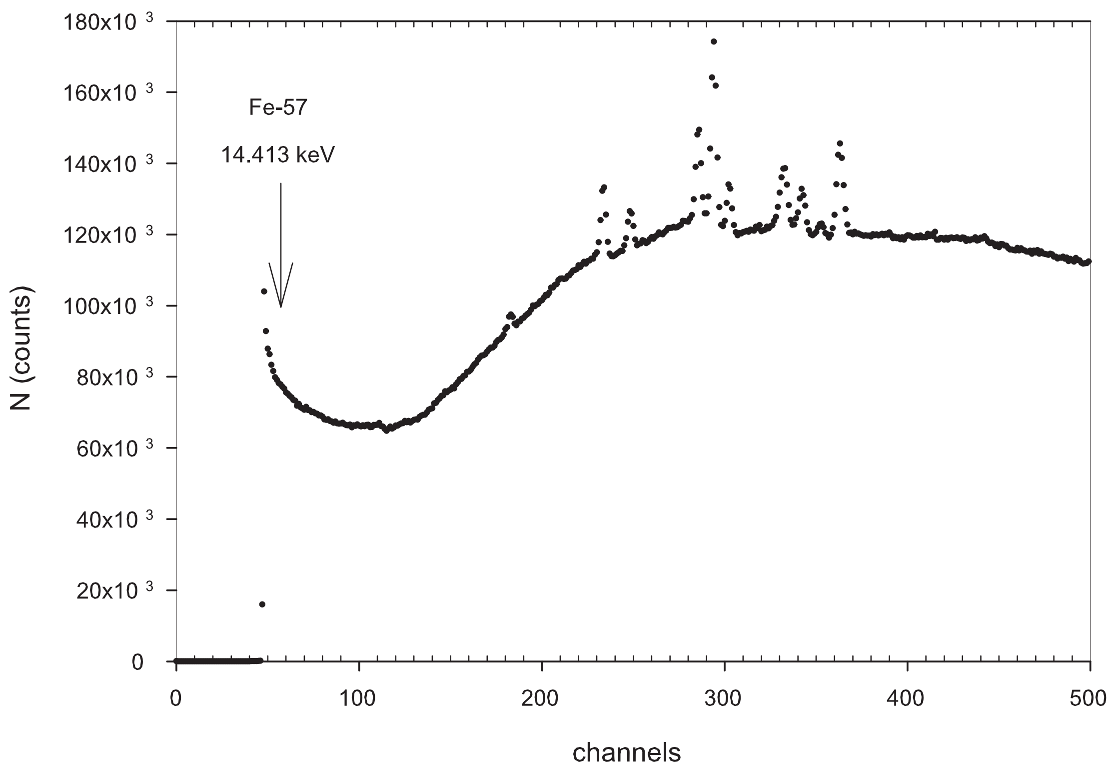

Fe-57
14.413 keV
N (counts)
channels
0
20x10 3
40x10 3
60x10 3
80x10 3
100x10 3
120x10 3
140x10 3
160x10 3
180x10 3
0
100
200
300
400
500